Statistical characteristics of the observed metal systems and problems of reionization

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ABSTRACT
We analyze basic properties of about 200 metal systems observed in high resolution spectra of 9 quasars by Boksenberg, Sargent & Rauch (2003). The measured Doppler parameters for the hydrogen and carbon lines are found to be different by a factor $\sim \sqrt{m_C/m_H}$ what indicates the domination of the thermal broadening and high degree of relaxation for majority of the observed metal systems. The analysis of the mean separation of the metal systems confirms that they can be located in regions with the typical proper size $R_{cl} \sim 0.1 - 0.25 h^{-1}$ Mpc what corresponds to the typical sizes of protogalaxies with the baryonic masses $M_b \approx 10^9 - 10^{10} M_\odot$. The metal abundances observed at redshifts $z = 3 - 6$ within both IGM and galaxies are found to be quite similar to each other what indicates the strong interaction of young galaxies with the IGM and the important role of dwarf satellites of host galaxies in such interaction. On the other hand, this metal abundance can be considered as the integral measure of nuclear reactions within any stars what in turn restricts the contribution of the stars to the creation of ionizing UV background. Available now estimates of these abundances demonstrate that attempts to explain the reionization of the Universe as a byproduct of the process of synthesis of metals only are problematic and a significant contribution of unobserved and/or non thermal UV sources seems to be required.

Key words: cosmology: reionization of the Universe — quasars: absorption: metal abundance.

1 INTRODUCTION

One of the most promising way to study the earlier stages of the process of galaxy formation and reionization of the Universe is the analysis of the Ly–α forest and metal systems observed in spectra of the farthest quasars. The great potential of such approach was discussed already by Oort (1981, 1984) just after Sargent et al. (1980) established the intergalactic nature of the forest. Indeed, the majority of HI absorbers are associated with the small scale distribution of intergalactic matter (IGM) along the line of sight at redshifts $z \geq 2$, when the IGM is not yet strongly clustered and its observed characteristics can be more easily interpreted. In turn, the observed metal systems are evidently associated with galaxies and they characterize the rate of galaxy formation and their environment. The available Keck and VLT high resolution observations of the absorption lines provide a reasonable database and allow one to apply statistical methods for their analysis. This analysis can be also supplemented by comparison of basic properties of metal systems with those available for galaxies at corresponding redshifts. These problems were discussed in many papers (see, e.g., Bergeron et al. 1992; Lanzetta et al. 1995; Tytler 1995; Le Brune et al. 1996) and more recently in Boksenberg, Sargent & Rauch (2003); Adelberger et al. (2005b) and Scannapieco et al. (2006).

The enrichment of the IGM by metals can be related to the starburst driven outflows (Pettini et al. 2001; Frye, Broadhurst & Benitez 2002) from the main galaxy or its dwarf satellites and to the stripping of these satellites. Both these processes occur but their efficiency is different. Thus, rare richer multicomponent systems are usually associated with the periphery of massive galaxies (see, e.g., Adelberger et al. 2005b; Songaila 2006). Their complex structure demonstrates that they were formed by a multi step process that involved both explosive and stripping metal injections. On the contrary, the commonly encountered poorer metal systems that are related to extended low density clouds are more probably linked with the dwarf satellites of the central

galaxy. Detailed discussion of this problem can be found in Scannapieco et al. (2006).

The comparison of Doppler parameters measured for the HI and metals in the same absorption systems allows also to compare the influence of the IGM temperature and the macroscopic motions on the structure of the clouds, to evaluate the degree of relaxation of compressed matter and to select the small fraction of clouds with the domination of supersonic macroscopic motions.

The separate problem is the process of reionization of the Universe. Observations of the farthest quasars (Becker et al. 2001; Djorgovski et al. 2001; Fan et al. 2004) show that the reionization of the IGM had just been completed at $z \sim 6 - 7$. On the other hand, the measurements of temperature fluctuations of the CMB by WMAP (Hinshaw et al. 2006) suggest that the reionization of the IGM has began at least at $z \sim 10 - 12$. Simulations indicate that the first stars and supernovae can be formed already at $z \sim 40 - 50$ (Reed et al. 2005) but for the standard cosmological model at $z \geq 10$ the fraction of matter accumulated by high density objects ("galaxies") is negligible ($\leq 10^{-6}$) and therefore reionization earlier than at $z \geq 10$ requires some exotic sources of the UV radiation such as, for example, antimatter or unstable particles (see, e.g, Cohen, De Rujula, Glashow 1998; Bambi & Dolgov 2007; Freese et al. 2007).

It is commonly believed that the general features of the reionization process are already established with a reasonable reliability (see, e.g., Tumlinson et al. 2004; Madau 2007; Schaerer 2007). At $z \leq 3.5 - 4$ the observed radiation of quasars dominates the UV ionizing background, but it provides not more than $20 - 30\%$ of the UV background at $z \geq 5$. Now it is expected that the UV radiation required for the reionization can be produced by the joint action of galaxies dominated by Population III and Population II stars (see, e.g., Tumlinson et al. 2004; Schaerer 2007) and by sources of non thermal radiation such as AGNs, miniquasars or black holes (see, e.g., Madau & Rees 2001; Meiksin 2005). However, the relative contribution of stars, gamma ray bursts (GRBs) and/or non thermal sources of UV radiation has not been determined yet. Now the main discussed problems are focused on indirect estimates and observational restrictions of efficiency of such sources (see, e.g., Dijkstra, Haiman & Loeb 2004; Meiksin 2005; Choudy et al. 2007) and the analysis of their interaction with the environment (see, e.g., Iliev, Shapiro & Raga 2004).

However we still have not seen neither the Pop III stars nor the first galaxies dominated by such stars and, so, the actual properties of such objects remain unknown. It seems that all galaxies observed at high redshifts –including both the Ly–breack galaxies (LBGs) and Ly–α emitters (LAEs) – are dominated by the Pop II stars, and only small part of LAE demonstrate some features expected for the first galaxies. Because of this it can be expected that the domination of Pop III stars could take place during only a short period of evolution of the first galaxies and these stars acts as a trigger for the faster formation of Pop II stars and for the transformation of the first galaxies into the LAEs and LBGs (Schneider et al. 2002; Ricotti & Ostriker 2004; Smith & Sigurdsson 2007; Tornatore et al. 2007; Karlsson et al. 2007). Thus the actual properties of the first galaxies could be quite similar to the observed properties of the LBGs and LAEs and the contribution of stars (and particularly of the

Pop III stars) to the production of the ionizing UV background and the process of reionization can be quite limited (see, e.g., Shull & Venkatesan 2007) while the contribution of alternative non thermal sources of UV luminosity can be essential.

Special problem is the existence of significant population of LAEs at redshifts $z \leq 5 - 6$. It is evident that the life time of envelopes of HI surrounding these galaxies is finite owing to the combine action of the observed outer UV background and internal sources of UV radiation. For the same reasons the recent formation or successive reconstruction of such envelops from the highly ionized IGM seem to be quite problematic. On the other hand, if LAEs represent special population formed from low ionized IGM at high redshifts then it is necessary to explain the unexpectedly slow evolution of survived objects. In this case a clear redshift variations of the number density of LAEs and their observed properties should be observed.

Here we analyze the sample of 908 high resolution CIV absorbers presented in Boksenberg, Sargent & Rauch (2003) and compare the measured properties of CIV and HI lines. This approach allows us to demonstrate that the majority of metal systems are associated with relaxed clouds. Our indirect estimates of the sizes of metal systems are consistent with direct measurements of Adelberger et al. (2005b) and Scannapieco et al. (2006). Our estimates of the CIV abundance in the IGM are similar to that observed within LBGs and LAEs, what demonstrates the important contribution of dwarf galaxies in the reionization. At the same time, the estimates of the metal abundance show that the radiation of stars only cannot reionize the Universe and the contributions of these stars and non thermal sources can be at least comparable.

In this paper we consider the spatially flat ΛCDM model of the Universe with the Hubble parameter and mean density given by:

$$H^2(z) = H_0^2 \Omega_m (1+z)^3 [1\Omega_\Lambda/\Omega_m (1+z)^{-3}] \,,$$

$$\langle n_b(z) \rangle = 2.4 \cdot 10^{-7} (1+z)^3 (\Omega_b h^2/0.02) \mathrm{cm}^{-3} \,, \tag{1}$$

$$\langle \rho_b(z) \rangle = \frac{3H_0^2}{8\pi G} \Omega_b (1+z)^3 \approx 4.8 \cdot 10^9 (1+z)^3 \frac{\Omega_b h^2}{0.02} \frac{M_\odot}{\mathrm{Mpc}^3} \,,$$

$$\langle \rho_m(z) \rangle = \frac{3H_0^2}{8\pi G} \Omega_m (1+z)^3, \quad H_0 = 100h \, \mathrm{km/s/Mpc} \,.$$

Here $\Omega_m = 0.3 \, \& \, \Omega_\Lambda = 0.7$ are the dimensionless density of matter and dark energy, $\Omega_b \approx 0.02$ and $h = 0.7$ are the dimensionless mean density of baryons, and the Hubble constant. For $z \geq 1$ the influence of Λ–term in (1) becomes negligible and we will write the Hubble parameter as

$$H(z) \approx H_0 \sqrt{\Omega_m} (1+z)^{3/2} \,. \tag{2}$$

2   THE DATABASE

The present analysis is based on 9 high resolution spectra listed in Boksenberg, Sargent & Rough (2003). The full sample of metal systems contains 908 CIV lines majority of which represent the internal structure of rich metal systems. From these spectra we select 193 metal systems at $2 \leq z \leq 4.4$. For 93 of these systems we have also parameters of the HI absorbers.
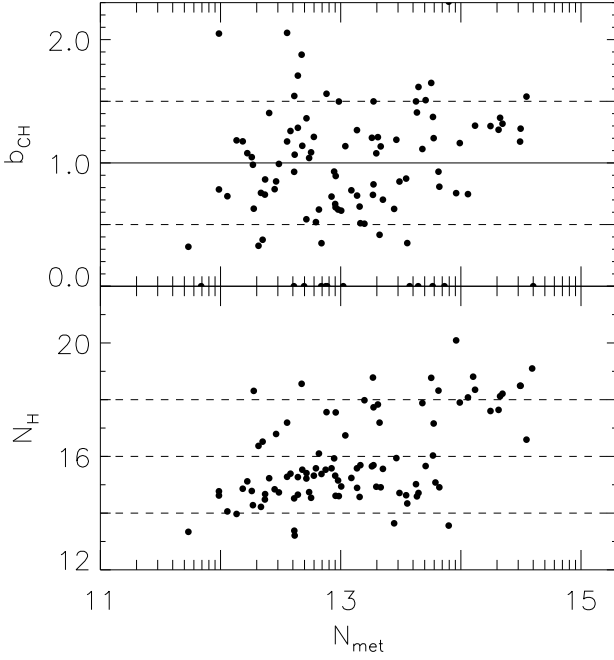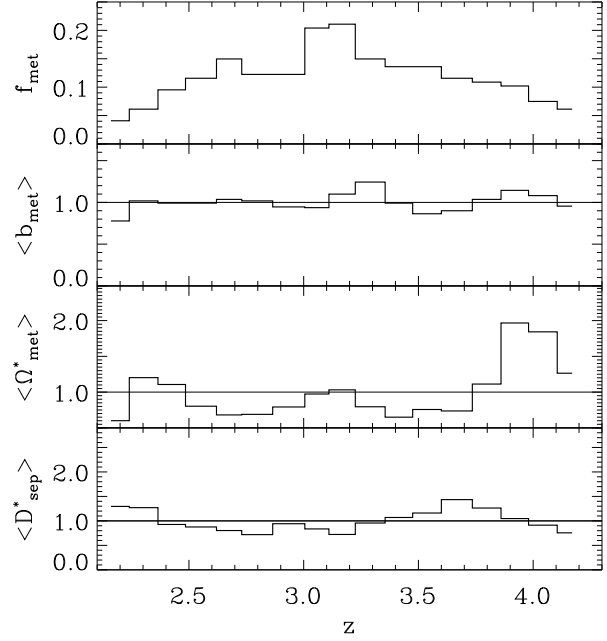
Figure 1. For the sample of 93 metal systems with $N_H > 0$ functions $b_{CH} = \sqrt{m_C/m_H}\, b_{met}/b_H$, and N_H are plotted vs. N_{met}.

Figure 2. For the sample of 154 metal systems the redshift distribution of the metal systems, f_{met}, the mean Doppler parameter, $\langle b_{met}\rangle$, the mean carbon abundance in the IGM, $\langle \Omega_C^*\rangle = \langle \Omega_C z_4^2\rangle$ and the mean system separation, $\langle D_{sep}^*\rangle = \langle D_{sep} z_4^{1.75}\rangle$ are plotted vs. redshift z.

As is seen from Fig. 1 the hydrogen and carbon column densities are weakly correlated and even for richer hydrogen absorbers with $N_{HI} \geq 10^{16} cm^{-2}$ there are metal systems with $2 \cdot 10^{12} cm^{-2} \leq N_C \leq 6 \cdot 10^{14} cm^{-2}$. 154 systems with $N_{HI} \leq 10^{16} cm^{-2}$ and $N_{CIV} \leq 10^{14} cm^{-2}$ can be related to the intergalactic ones while 32 systems with $N_{HI} \geq 10^{16} \mathrm{cm}^{-2}$ are probably linked with intervening galaxies. The separation of these metal systems can be compared with results obtained for 268 publicly available metal systems observed with intermediate resolution.

As is seen from Fig. 2, the redshift distribution of the metal systems is non homogeneous and the majority of systems are concentrated at $2 \leq z \leq 3.5$. This means that some of the discussed here characteristics are derived mainly from this range of redshifts. At $z \geq 3.5$ the statistics of lines is not sufficient. Detailed discussion of the observed characteristics of these metal systems can be found in Boksenberg, Sargent & Rough (2003).

3 OBSERVED CHARACTERISTICS OF METAL SYSTEMS

The sample of 154 metal systems with $N_C \leq 10^{14} cm^{-2}$, and $N_H \leq 10^{16} cm^{-2}$ can be used to characterize the metal systems actually related with the IGM. For this sample the redshift variations of the four mean observed characteristics, namely, the column density of CIV, $\langle N_C\rangle$, the Doppler parameter, $\langle b_{met}\rangle$, the mean abundance of carbon in the IGM, $\langle \Omega_C\rangle$, and the mean separation of metal systems, $\langle D_{sep}\rangle = \langle D_{sep}^* z_4^{-1.75}\rangle$, $z_4 = (1)/4$ are plotted in Fig. 2 for $2 \leq z \leq 4$. Here the mean abundance of the carbon in IGM is estimated as follows,

$$\langle \Omega_C\rangle = \left\langle \frac{m_C N_C}{D_{sep}} \frac{8\pi G}{3H_0^2}\right\rangle .$$

The redshift variations of these parameters are fitted by expressions

$$\langle b_{met}\rangle = (11.2 \pm 1)\mathrm{km/s},$$

$$\langle N_C^*\rangle = \langle N_C z_4^2\rangle = 3 \cdot 10^{13}(1 \pm 0.3)cm^{-2}, \quad z_4 = (1)/4,$$

$$\langle \Omega_C^*\rangle = \langle \Omega_C z_4^2\rangle = [4 \pm 2]h^{-1} \cdot 10^{-8}\sqrt{\Omega_m/0.3}, \tag{3}$$

$$\langle D_{sep}^*\rangle = \langle D_{sep} z_4^{1.75}\rangle = (27.4 \pm 5.8)h^{-1}\sqrt{0.3/\Omega_m}\ \mathrm{Mpc},$$

respectively. These estimates are consistent with those obtained in Boksenberg et al. (2003) for 'complex systems'. They are also quite similar to the estimates of Scannapieco et al. (2006) and Songaila (2001). For all 193 systems the mean separation decreases to

$$\langle D_{sep}^*\rangle = \langle D_{sep} z_4^{1.75}\rangle = (23.8 \pm 3.4)h^{-1}\sqrt{0.3/\Omega_m}\mathrm{Mpc}. \tag{4}$$

For 32 systems with $N_{HI} \geq 10^{16} cm^{-2}$ which can be related to intervening galaxies the hydrogen and metals abundance increase up to:
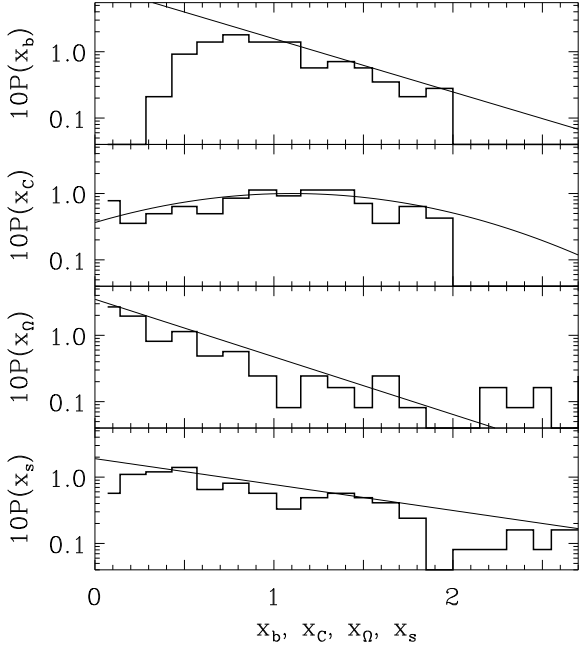
$$\langle \lg N_C/N_{HI}\rangle = -4.2 \pm 0.6, \quad \langle \lg N_C\rangle = 14 \pm 0.4, \tag{5}$$

what indicates the low concentration of carbon as compared with its solar abundance $(\lg N_C/N_{HI})_\odot \approx -3.5$ (Allende Prieto et al. 2002). The mean separation of these objects is

$$\langle D_{sep}^*\rangle = \langle D_{sep} z_4^{1.75}\rangle = (93 \pm 24)h^{-1}\sqrt{0.3/\Omega_m}\mathrm{Mpc},$$

what substantially exceeds the previous ones. For 26 Ly–limit systems with $N_{HI} \geq 10^{17} cm^{-2}$ this separation increases up to

$$\langle D_{sep}^*\rangle = \langle D_{sep} z_4^{1.75}\rangle = (111 \pm 31)h^{-1}\sqrt{0.3/\Omega_m}\mathrm{Mpc}, \tag{6}$$

Figure 3. For the sample of 193 metal systems PDFs for the Doppler parameter, $P(x_b)$, the carbon column density, $P(x_C)$, and abundance, $P(x_\Omega)$, and the separation of metal systems, $P(x_{sep})$, are plotted together with fits (7).

and the carbon abundance drops down to

$$\langle \lg N_C/N_{HI} \rangle = -4.6 \pm 0.2 .$$

For the 268 metal systems selected from spectra observed with intermediate resolution the mean separation is similar to (6).

The observed probability distribution functions, PDFs, for the Doppler parameter, $P(b)$, the carbon column density, $P(N_C z_4^2)$, the carbon abundance, $P(\Omega_C)$, and the separation of metal systems, $P(D_{sep} z_4^{1.75})$, are plotted in Fig. 3. Such choice of variables allows us to suppress the artificial redshift variations of the PDFs caused by the redshift evolution of the mean characteristics of these systems. These PDFs are well fitted by the following functions

$$P_{fit}(x_C) \approx \exp[-(x_C - 0.8)^2/1.2], \quad x_C = \lg N_C/\langle \lg N_C \rangle ,$$

$$P_{fit}(x_b) \approx \exp(-1.85 x_b), \quad x_b = b_{met}/\langle b_{met} \rangle \geq 1 ,$$

$$P_{fit}(x_\Omega) \approx 3.5 \exp(-2 x_\Omega), \quad x_\Omega = \Omega_C z_4^2/\langle \Omega_C z_4^2 \rangle , \qquad (7)$$

$$P_{fit}(x_s) \approx 1.9 \exp(-x_s), \quad x_s = D_{sep} z_4^{1.75}/\langle D_{sep} z_4^{1.75} \rangle ,$$

where again $z_4 = (1)/4$.

For the sample of 193 metal systems the main fraction of observed systems ($\sim 70\%$) is linked with rich absorbers with $\lg(N_{HI}) = 15 \pm 1$ and only 10% of systems can be related to the Lyman–limit systems with $\lg(N_{HI}) \geq 17$. At the same time, 75% of absorbers with $\lg(N_{HI}) \geq 14$ do not contain metals above the measured limit $\lg(N_C) \approx 12$. These results confirm that the observed pollution of the IGM is caused by rare sources of metals.

It is interesting also to compare the separations of metal systems with different richness. Thus for subsamples of 91 poorer systems with $N_c \leq 10^{13} cm^{-2}$ and 102 richer systems

with $N_c \geq 10^{13} cm^{-2}$ the mean separations are quite similar, $\langle D_{sep} z_4^{1.75} \rangle \sim 32 h^{-1} \mathrm{Mpc}$. This result is well consistent with the mean separation obtained for the full sample of 193 systems (4). It emphasises similarity in the spatial distributions of poorer and richer systems concentrated within rare clouds.

In spite of limited range of observed redshifts and the large scatter of estimates (3), growth with time of $\langle \Omega_C \rangle$ and $\langle N_C \rangle$ points out to the progressive enrichment of IGM by metals. These results are consistent with those obtained by Boksenberg et al. (2003) and Scannapieco (2006) and can be related to the evolution of galaxies at the same redshifts. However, Songaila (2001) observed very slow redshift variations of the carbon abundance $\Omega_C \simeq (5.2 \pm 1.7) \cdot 10^{-8}$ at $2 \leq z \leq 5.5$ while Schaye et al. (2003) discussed the slow evolution of unexpectedly high carbon abundance $\Omega_C \approx 2 \cdot 10^{-7}$.

At the same time, the weak redshift variations of both $\langle N_C \rangle$ and N_C/N_{HI} (5) indicate that for the stronger systems related to the intervening galaxies the carbon abundance is redshift independent. The properties of metal systems are very important for reconstruction of galaxy evolution at high redshifts and they deserve more detailed observational investigation.

4   DISCUSSION

Results presented in previous Section allow us to test the degree of relaxation of matter compressed within such absorbers and to obtain indirect estimates of spatial characteristics of metal systems. Finally we can estimate the possible contribution of stars and the process of metal production to the radiation that reionized the Universe.

4.1   Degree of absorbers relaxation

Comparison of the Doppler parameters of metal systems, b_{met}, and accompanied hydrogen lines, b_H, allows to clarify the complex problem of the internal structure of absorbers. Thus, numerical simulations show that absorbers can be relaxed along one or two shorter axes and the width of the absorption lines depends upon the thermal broadening, b_T, the differential Hubble flow, b_{Hu}, and turbulent macroscopic velocities, b_{mt},

$$b = \sqrt{b_T^2 + b_{Hu}^2 + b_{mt}^2} .$$

where $b_T \propto m_i^{-1/2}$ depends upon the mass of ion, m_i, while two other components are the same for all ions.

The relative contribution of these factors varies from absorber to absorber (see, e.g., Theuns, Schaye & Haehnelt 2000; Schaye 2001). For majority of absorbers the possible contribution of Hubble flow is naturally linked with the retained expansion of clouds and is more essential for weaker absorbers. Its contribution depends upon the (unknown) relative orientation of absorber expansion and the line of sight. On the other hand, the supersonic macroscopic motions are rapidly transformed to the shock waves and so they disappear. Their life time is relatively short and existence over an extended period is quite problematic what implies that $b \leq \sqrt{2} b_T$ is a more probable result.

Comparison of the Doppler parameters of metal systems and accompanied hydrogen lines allows to discriminate between contributions of thermal and various large scale bulk and turbulent motions. Indeed, macroscopic and turbulent velocities are the same for all ions and in that case we can expect that

$$b_H \approx b_C, \quad b_{ch} = \sqrt{m_C/m_H} b_C/b_H \sim \sqrt{12} \approx 3.5 \,. \quad (8)$$

On the contrary, for any given temperature of the gas the thermal velocities of ions depend upon their masses and in this case b_{ch} determined by (8) should be close to one.

For 93 systems plotted in Fig 1 comparison of these Doppler parameters shows that

$$\langle b_{ch} \rangle = \sqrt{m_C/m_H} \langle b_C/b_H \rangle \approx 1.1 \pm 0.5 \,, \quad (9)$$

and only for 8 absorbers $2 \geq b_{ch} \geq 1.5$. This result indicates that the thermal velocities dominate within majority of absorbers in the sample, $b_T \geq b_{mt}$. As is seen from Fig. 1 a scatter of this ratio increases for small $N_C \leq 10^{13} cm^{-2}$ what indicates smaller degree of relaxation for poorer metal systems. This scatter increases if the pollution of IGM is caused by the ejection of metals from closest galaxies when the remaining velocity of ejection increases the Doppler parameter of metals and makes it larger than that for the hydrogen component (see, e.g., Songaila 2006).

These results imply the approximate hydrostatic equilibrium of compressed matter along the line of sight or at least along the shorter axis of clouds and agree well with inferences of Carswell, Schaye & Kim (2002); Telfer et al. (2002); Simcoe, Sargent & Rauch (2002), (2004); Boksenberg, Sargent and Rauch (2003); Bergeron & Herbert-Fort (2005). In particular, comparison of the Doppler parameters measured for HI, CIV and OVI (Carswell, Schaye & Kim 2002) verifies also that as a rule the macroscopic (turbulent) velocities are subsonic.

These observational results strongly suggest that most absorbers are long–lived partly gravitationally bound and partly relaxed and they are composed of both DM and baryonic components.

4.2   Links between metal systems and galaxies

Natural links between the metal systems and galaxies was confirmed by direct observations by Adelberger (2005a, b), where for majority of systems with $N_C \sim 10^{14} cm^{-2}$ the proper sizes of absorbing regions at $z = 2-3$ were estimated as $R_{abs} \sim 0.08 \mathrm{Mpc}$ for CIV lines and as $R_{abs} \sim 0.4 \mathrm{Mpc}$ for OVI lines. At the same time, Scannapieco et al. (2006) found that the metal systems are clustered within "bubbles" with the comoving size $R_{bb} \sim 2h^{-1}\mathrm{Mpc}$. Analysis of the observed absorber separations allows us to test these results.

The mean comoving separation of clouds is determined as

$$\langle D_{sep} \rangle = \left\langle \frac{1+z}{3n_{cl}(z)S_{cl}(z)} \right\rangle \,, \quad (10)$$

where $n_{cl}\, \& \, S_{cl}$ are the proper number density and surface area of the clouds projection on the sky. For the metal systems with $N_{HI} \geq 10^{16} cm^{-2}$ we have $\langle D_{sep} \rangle \approx 100 z_4^{-1.75} h^{-1} \mathrm{Mpc}$. It can be expected that such systems are related to gravitationally bounded intervening galaxies and

for them S_{cl} only weakly depends on redshift, $S_{cl} \approx const.$ Therefore, for such systems $\langle n_{cl} \rangle \propto (1+z)^{2.75}$ what implies that at redshifts $z \sim 2-4$ the comoving number density of galaxies increases with time as $n_{gal} \propto (1+z)^{-0.25}$. Comparison of the observed number density of galaxies in the SDSS and 2dF surveys (Doroshkevich et al. 2004)

$$\langle n_{gal}(z=0) \rangle \sim 10^{-2} h^3 \mathrm{Mpc}^{-3} \,, \quad (11)$$

and of LBG galaxies at $z \sim 3$ (Adelberger 2005a),

$$\langle n_{gal}(z=3) \rangle \sim 4h^3 \cdot 10^{-3} \mathrm{Mpc}^{-3} \,, \quad (12)$$

indicates similar evolution, $n_{gal} \propto (1+z)^{-1/2}$. Using (6 & 12) we get for the proper mean surface area and size of such metal systems

$$\langle S_{cl} \rangle \sim 0.05 h^{-2} \mathrm{Mpc}^2, \quad \langle R_{cl} \rangle = \sqrt{S_{cl}/\pi} \sim 0.12 h^{-1} \mathrm{Mpc}\,. \quad (13)$$

This estimate is similar to the proper sizes of absorbing regions obtained by Adelberger (2005b) at $z = 2-3$ for CIV lines.

For weaker metal systems we can expect progressive growth of the proper cloud surface area with time, $\langle S_{cl} \rangle \propto (1+z)^{-\beta}$ and for $\beta \geq 0.25$ a successive decrease with time of their comoving number density $\langle n_{cl} \rangle \propto (1+z)^{\beta-0.25}$. This means that due to clouds expansion some fraction of the weak metal systems goes under the observational limit $N_C \leq 10^{12} cm^{-2}$. Such effect was found for the Ly-α forest (Demiański et al. 2006).

Using the estimate (3) for the mean system separation we get for the mean proper surface area and size of such systems

$$\langle S_{cl} \rangle \approx 0.2 h^{-2} z_4^{-\beta} Mpc^2, \quad \langle R_{cl} \rangle \approx 0.25 h^{-1} z_4^{-\beta/2} Mpc\,, \quad (14)$$

where $z_4 = (1+z)/4$. This estimate of R_{cl} is of about two – three times smaller than the values found by Adelberger et al. (2005b) for weak lines OVI and the comoving size of "bubbles", $R_{bb} \sim 2h^{-1}\mathrm{Mpc}$, found by Scannapieco et al. (2006) at redshifts $z = 2-3$.

Formation of galaxies with the baryonic mass M_b implies accumulation of matter from the protogalaxy with the proper size

$$R_{prg} \approx (6V/\pi)^{1/3} \approx 0.4 z_4^{-1} Mpc \left[\frac{M_b}{10^{10} M_\odot} \frac{0.02}{\Omega_b h^2} \right]^{1/3} \,, \quad (15)$$

what quite well agrees with (14 for $M_b \sim 10^9 M_\odot$ and with observations of Adelberger et al. (2005b) and Scannapieco et al. (2006) for $M_b \sim 10^{10} M_\odot$.

Now the pollution of IGM by metals is related either to ejection of metals from galaxies after explosions of supernovae or to the stripping of satellites of the central galaxy. It is most probable that both processes are equally important. Thus, as was noted in Sec. 3.2, the complex structure of richer systems implies the multistep metal ejection what is naturally connected with SN explosions in the large central galaxy. On the contrary, at large distances from the central galaxy ejection of metals from satellites and their stripping dominate.

The pronounced correlation between the observed galaxies and metal systems reflects the expected interaction between the large and small scale perturbation when former ones modulate the process of galaxy formation and amplify the inhomogeneities in the spatial galaxy distribution. At the same time, the noted above similarity in the

spatial distributions of richer and poorer metal systems indicates similarities in their genesis and their close links with the ordinar observed galaxies.

4.3 Probable sources of reionization

Measurements of the carbon abundance in the IGM at high redshifts allows us to clarify some aspects of the process of reionization of the Universe. Thus, the concentration of metals in the older galaxies observed at redshifts $z \sim 6 - 7$ and higher is the integral measure of the contribution of nuclear reactions within any stars to the creation of the ionizing UV radiation. On the other hand, the comparison of the carbon abundances within galaxies and in the IGM characterizes the efficiency of the processes of star explosion and ejection of metals from the host galaxies and their dwarf satellites. It is important that this approach estimates the integral action of all stellar sourses ignoring the often discussed (see, e.g. Choudhury et al. 2007) but badly known details of the reionization process such as the mass function of the first galaxies and Pop. III stars, the rate of the star creation, radiative feedback or the redshift variations of the transmitted flux and the electronic depth.

4.3.1 Contribution of observed galaxies

As is well known, the transformation of hydrogen to carbon produces $\approx 7.3 MeV$ of energy per one baryon what is equivalent to $N_\gamma \approx 5 \cdot 10^5$ of UV photons with energy $E_\gamma \approx 13.6 eV$. The synthesis of O, N, Si and other metals produces the UV radiation with the similar efficiency. According to more detailed estimates (see, e.g., Tumlinson et al. 2004) the value of ionizing photons per one baryon is smaller and varies with the mass of Pop. III stars in the range $N_\gamma \simeq (2 - 8) \cdot 10^4$.

At the same time, the observed strong ionization of hydrogen at $z = 5 - 7$ implies the generation already at such redshifts of at least one UV photon per baryon ($N_{b\gamma} \geq 1$). Of course, this is the minimal value and in some papers (see, e.g. Dijkstra, Haiman, Loeb 2004; Madau 2007) production of extra (up to 10) UV photons per baryon is discussed. Thus, if the reionization was caused by the production of metals within stars then the minimal abundance of metals at $z \sim 6$ must be at least

$$\Omega_{min} \simeq \frac{\Omega_b N_{b\gamma}}{f_{esc} N_\gamma} \approx 0.8 \cdot 10^{-7} \frac{N_{b\gamma}}{f_{esc}} \frac{5 \cdot 10^5}{N_\gamma} \frac{\Omega_b}{0.04}, \qquad (16)$$

where $N_{b\gamma} \geq 1$ is the minimal number of UV photons per one baryon required for the reionization and $f_{esc} \leq 1$ is the mean fraction of UV photons escaping from galaxies. The allowance for the complex spectral distribution of the generated UV photons, ionization of He and the heating and slow recombination of the IGM increases this estimate of the Ω_{min} by a factor of $2 - 3$.

Available now estimates of the stellar component in galaxy populations observed at redshifts $z \geq 3$ are summarized in Table 1. Here observations of Lai et al. (2007) relate to the two populations of LAEs (younger and older) and the scatter of measured ρ_* is determined by variations of the selected samples of galaxies.

The most interesting estimates for our goals came from recent observations of 11 galaxies by Wiklind et al.

Table 1. Galaxies at $z \geq 3$

$\langle z \rangle$	M_* $10^9 M_\odot$	ρ_* $10^6 M_\odot \mathrm{Mpc}^{-3}$	Ref.
~ 3	0.1	0.3	Lai et al. (2007)
~ 3	1	3.	Lai et al. (2007)
~ 5	1	1.5	Verma et al. (2007)
~ 6	1	1 - 7	Yan et al. (2006)
~ 6	10	2.5	Eylis et al. (2007)
$\sim 5-6$	50 - 500	8.	Wiklind et al. (2007)
~ 7	1-10	1.6	Labbe et al. (2006)

M_* and ρ_* are the mean stellar mass and the stellar mass density for the observed sample of galaxies.

(2007) (Table 1) which are related to older massive compact galaxies with the comoving number density $n_{gal} \approx 1.4 \cdot 10^{-5} \mathrm{Mpc}^{-3}$, the proper sizes $R_g \sim 2 \mathrm{kpc}$ and ages 0.2–1 Gyr. It is expected that the majority of these stars were formed at $z \geq 9$ and they represent the objects actually responsible for the reionization.

For this sample of galaxies we get for the stars and metal abundances

$$\Omega_* \approx 6.7 \cdot 10^{-5}, \quad \Omega_{*met} = \Omega_* Z \approx 1.3 \cdot 10^{-7} \frac{Z}{0.1 Z_\odot}, \qquad (17)$$

and Ω_* is significantly below the present day values $\Omega_{lum}(z = 0) \approx 4 \cdot 10^{-3}$ (Fukugita et al. 1998). It is evident that this result is consistent with Ω_{min} (16) only for an unlikely value $N_{b\gamma}/f_{esc} \sim 1$.

On the other hand, any such galaxy can ionize baryons in a volume with the mass M_i and comoving size R_i where

$$M_i \sim 20 \epsilon_{eff} M_*, \quad \epsilon_{eff} = \frac{f_{esc}}{0.1} \frac{Z}{0.1 Z_\odot} \frac{N_\gamma}{5 \cdot 10^5}, \qquad (18)$$

$$R_i = \left(\frac{3 M_i}{4\pi \langle \rho_b \rangle} \right)^{1/3} \sim 5.5 \mathrm{Mpc} \left(\epsilon_{eff} \frac{M_*}{10^{11} M_\odot} \frac{0.02}{\Omega_b h^2} \right)^{1/3}.$$

So the moderate size of ionized bubble corresponds to the small fraction of the ionized IGM,

$$f_i = M_i n_{gal} / \langle \rho_b \rangle \sim 10^{-2} \epsilon_{eff} \frac{M_*}{10^{11} M_\odot} \frac{0.02}{\Omega_b h^2}, \qquad (19)$$

what illustrates the limited efficiency of ionization caused by the nuclear reactions within such galaxies. Of course, as was noted above, at redshift $z = 3$ the density of LBG galaxies (12) is larger by a factor of 10^2 but for them $M_* \ll 10^{11} M_\odot$ (Table 1) and finally we get again $f_i \ll 1$.

Estimates of the star radiation (16, 19) include the factor f_{esc}. Its available estimates are quite uncertain as they strongly depend upon the internal structure of galaxy and the immediate environment of the UV sources. These estimates vary from $f_{esc} \sim 2 - 3\%$ to $f_{esc} \sim 10\%$ (Iliev et al. 2004; Dijkstra et al. 2004; Meiksin 2005). For example, for the observed LAEs $f_{esc} \to 0$ and so majority of the UV radiation is absorbed within the galaxy. Thus, we can conclude that either all observations cited above and Eq. (17) strongly underestimate the metal production and the UV radiation of high redshifts galaxies or the reionization is related with some unobserved thermal and/or non thermal sources of UV radiation.

4.3.2 Possible contribution of dwarf galaxies

The differences between estimates (16) and (17) will decrease if the majority of ionizing UV radiation is related with the dwarf unobserved galaxies. Such preferential formation of dwarf galaxies is natural in the CDM cosmology and is consistent with observations (see, e.g., Yan & Windhorst 2004; Yan et al. 2006; Stark et al. 2007). It is also consistent with the shape of the UV luminosity function observed at redshifts $z = 4 - 6$ (Bouwens et al. 2007). Moreover, reconstruction of the initial power spectrum in Demiański et al. (2006) indicates the possible excess of power at scales $M \leq 10^8 M_\odot$ what can additionally stimulate earlier formation of dwarf galaxies.

The contribution of dwarf galaxies is also restricted owing to the observational limitations for the small fraction of dwarf galaxies survived at $z = 0$ (see also Adelberger 2005a). Non the less, the important role of dwarf galaxies in the reionization is supported by the observed abundance of CIV in the IGM. All published estimates of carbon abundance at redshifts $3 \leq z \leq 5.5$ are close to $\Omega_C \approx (5.2 \pm 1.7) \cdot 10^{-8}$ (Songaila 2001; Pettini et al. 2003; Boksenberg et al. 2003; Scannapieco et al. 2006; Ryan-Weber et al. 2007) and are consistent with (3) in the range of scatter. The slow redshift evolution of the abundance implies that the main enrichment of the IGM takes place at high redshifts $z \geq 6$. Moreover, the carbon abundance in the IGM is also close to that observed in galaxies at the same redshifts (17)

$$\Omega_{*C} = \Omega_{*met} Z_C / Z_{met} \simeq 0.2 \Omega_{*met} \simeq 2.6 \cdot 10^{-8}\,. \quad (20)$$

As was noted in the previous subsection these metals are presumably concentrated within bubbles with the comoving size $\sim 2h^{-1}$ Mpc. This size significantly exceeds the typical size ~ 2 kpc observed for galaxies at the same redshifts (Wiklind et al. 2007) but it is close to the size of protogalaxy with the baryonic mass $M_b \sim 10^{10} - 10^{11} M_\odot$. In turn, such patchy spatial distribution of metals in the IGM implies that the process of metal enrichment is dominated by metal ejection from the dwarf satellites of the host galaxy in the course of their hierarchical clustering. This inference is close to that formulated in Songaila (2006) where it was noted that the formation of weak CIV systems cannot be easily understood in terms of high velocity galactic wind. Observation of GRB at redshift $z = 6.3$ (Haislip et al. 2005) can be considered as a possible example of such processes. This discussion shows that the real metal abundance at $z \geq 6$ exceeds the estimate (17) at least by a factor of 2. On the other hand, such scenario implies also the existence at $z = 0$ of the invisible dwarf galaxies in the vicinity of massive galaxies of early types.

4.3.3 Possible contribution of nonthermal sources

This discussion shows that even taking into account all uncertainties of observations the attempts to explain the reionization as a consequence of nuclear reactions within stars seem to be highly problematic (see also Adelberger 2005a; Meiksin 2005). The non thermal sources of UV photons such as AGNs and black holes formed both in pregalactic systems and within first galaxies produce ~ 50Mev per one accreted baryon what is 7 times more effective than the nuclear reactions. This means that even accretion of a small fraction of baryons,

$$\Omega_{acr} \simeq 10^{-8}/f_{esc} \simeq 1.4 \cdot 10^{-4} \Omega_* / f_{esc}\,, \quad (21)$$

will produce the same effect as the observed stars (17). This verifies that such non thermal sources of UV radiation can be considered as very promising ones and that they can be actually responsible for the reionization (see, e.g., Madau & Rees 2001; Meiksin 2005; Reed 2005; Ciardi et al. 2006; Madau 2007).

The observational restrictions of such non thermal sources of the UV radiation are poor. Thus, Meiksin notes that the comoving space density of galaxies with the black holes is $n_{bh} \sim 2 \cdot 10^{-4}$Mpc^{-3} what is $\sim 1\%$ of galaxies at $z = 0$. However, this value is 10 times more than the comoving number density of early massive galaxies (Wiklind et al. 2007) which demonstrate some features of the AGN activity. A faint AGN was directly observed at $z = 5.44$ (Douglas et al. 2007). Restrictions of the contribution of such sources discussed in Dijkstra et al. (2004) were criticized by Meiksin (2005). The possible contribution of exotic sources such as the unstable fraction of DM particles or antimatter can be noticeable at $z \geq 20 - 30$ (Cohen et al. 1998; Bambi & Dolgov 2007; Freez at al. 2007) but it cannot dominate at the period of recombination. Its possible impact will be soon tested by the Planck mission.

These problems are open for discussions but the important contribution of non thermal UV sources seems to be required. Further progress can be achieved with a richer and more refined sample of observed metal systems and earlier galaxies.

REFERENCES

Adelberger K., 2005a, Proceeding IAU Colloquium No.199, "Probing galaxies throwgh Quasar Absorption lines", IAU Colloquivium No.199, eds. P.Williams, C.Shu, and B.Menard, astro-ph/0504311

Adelberger K., Shapley A., Steidel C., Pettini M., Erb D., & Reddy N., 2005b, ApJ, 629, 636

Allende Prieto C., Lambert D., Asplund M., 2002, ApJ, 573, L137

Bambi C., Dolgov A., 2007, astro-ph/0702350

Becker R.H. et al. 2001, AJ, 122, 2850

Bergeron J., Cristiani S., & Shaver P.A., 1992, A&A, 257, 417

Bergeron J. & Herbert-Fort S., 2005, "Probing Galaxies through Quasar Absorption lines", IAU Colloquivium No.199, eds. Williams P.R., Shu C., & Menard B.. astro-ph/0506700

Bouwens R., Illingworth G., Franx M., Ford H., 2007, arXiv:astro-ph/0707.2080v2

Boksenberg A., Sargent W.L.W., Rauch M., 2003, ApJS, submit. astro-ph/0307557

Carswell R., Shaye J., & Kim T.S., 2002, ApJ, 578, 43

Choudry R., Ferrara A., Gallerani S., astro-ph/0712.0738

Ciardi B., Scannapieco E., Stoehr F., Ferrara A., Iliev I., Shapiro P., 2006, MNRAS, 366, 689

Cohen A., De Rujula A., Glashow S., 1998, ApJ, 495, 539

Dijkstra M., Haiman Z., Loeb A., 2004, ApJ, 613, 646

Djorgovski S., Castro S., Stern D., Mahabal A., 2001, ApJ, 560, L5

Demiański M., Doroshkevich A., Turchaninov V., 2006, MNRAS,

Doroshkevich A., Tucker D.L., Allam S., Way M.J., 2004, AA, 418, 7

Douglas L., Bremer M., Stanway E., Lehnert M., 2007, MNRAS, 376, 1393

Eyles L., Bunker A., Ellis R., Lacy M., Stanway E., Stark D., Chiu K., 2007, MNRAS, 374, 910

Fan X. et al., 2004, AJ, 128, 515

Freese K., Gondolo P., Spolyar D., 2007, astro-ph/0709.2369

Frye B., Broadhurst T., Benitez N., 2002, ApJ, 568, 558

Fukugita M., Hogan C., Peebles P.J.E., 1998, ApJ, 503, 518

Hinshaw G. et al., 2007, ApJS, 170, 288

Haislip J., et al., 2006, Nature, 440, 181

Iliev I, Shapiro P., Raga A., 2005, MNRAS, 361, 405

Labbe I., Bouwence R., Illingworth G., Franx M., 2006, ApJ, 649, L67

Lai K. et al., 2007, arXiv:astro-ph/0710.3384v1

Lanzetta K.M., Bowen D.V., Tytler D., & Webb J.K., 1995, ApJ., 442, 538.

Le Brune V., Bergeron J., & Boisse P., 1996, A&A, 306, 691

Madau P., Rees M., 2001, ApJ., 555, 9

Madau P., 2007, "The Emission Line Universe", eds. J. Cepa and N. Sanchez, Cambridge Unuversity Press, astro-ph/0706.0123

Meiksin A., 2005, MNRAS, 356, 596

Oort J.H., 1981, Astr.Astrophys., 94, 359.

Oort J.H., 1984, Astr.Astrophys., 139, 211.

Pettini M., Shapley A., Steidel C., Cuby J., Dickinson M., Moorwood A., Adelberger K., Giavalisco M., 2001, ApJ, 554, 981

Pettini M., Madau P., Bolte M., Prochska J., Ellison S., Fan X., 2003, ApJ, 594, 695

Reed D., Bower R., Frenk C., Gao L., Jenkins A., Theuns T., White S., 2005, MNRAS, 363, 393.

Ricotti M., Ostriker J.P., 2004, MNRAS, 350, 539

Ryan-Weber E., Pettini M., Madau P. 2006, MNRAS, 371, L78

Sargent, W.L.W., Young, P.J., Boksenberg, A. & Tytler, D., 1980, Ap.J.Suppl, 42, 41

Scannapieco E., Pichon C., Aracil B., Petitjean P., Thacker R., Pogosian D., Bergeron J., Couchman H., 2006, MNRAS, 365, 615; astro-ph/0503001

Schaerer D., 2007, "The Emission Line Universe", eds. J. Cepa and N. Sanchez, Cambridge Unuversity Press, astro-ph/0706.0139

Schaye J., 2001, ApJ, 559, 507

Schaye J., Aguirre A., Kim T.S., Theuns T., Rauch M., Sargent W.L.W., 2003, ApJ., 596, 768

Schneider R., Ferrara A., Natarajan P., Omukai K., 2002, ApJ, 571, 30

Shull M., Venkatesan A., 2007, arXiv:astro-ph/0702323

Simcoe R., Sargent W.L.W., Rauch M., 2002, ApJ., 578, 737

Simcoe R., Sargent W.L.W., Rauch M., 2004, ApJ., 606, 92

Smith B., Sigurdsson S., 2007, ApJ, 661, L5

Songaila A., 2001, ApJ, 561, L153

Songaila A., 2006, AJ., 131, 24

Stark D., Ellis R., Richard J., Kneib J., Smith G., Santos M., 2007, ApJ, 663, 10

Telfer R.C., Kriss G.A., Zheng W., Davidsen A.F. & Tytler D., 2002, ApJ, 579, 500

Theuns T., Schaye J., Haehnelt M., 2000, MNRAS, 315, 600

Tornatore L., Ferrara A., Schneider R., 2007, arXiv:astro-ph/0797.1433

Tumlinson J., Venkatesan A., Shull M., 2004, ApJ, 612, 602

Tytler D., 1995, in Meylan J., ed., QSO Absorption Lines, p. 289.

Verma A., Lehnert M., Förster Schneider N., Bremer M., Douglas L., 2007, MNRAS, 377, 1024

Wiklind T., Dickinson M., Ferguson H., Giavalisco M., Mobasher B., Grogin N., Panagia N., 2007, arXiv:astro-ph/0710.0406

Yan H., Windhorst R., 2004, ApJ, 600, L1

Yan H., Dickinson M., Giavalisco M., Stern D., Eisenhardt P., Ferguson H., 2006, ApJ, 651, 24